



## Measurement of Branching Fraction and $CP$ Asymmetry in $B \rightarrow \eta h$ Decays

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## Abstract

We report measurements of  $B$  to pseudoscalar-pseudoscalar decays with at least one  $\eta$  meson in the final state using  $140 \text{ fb}^{-1}$  of data collected by the Belle detector at KEKB  $e^+e^-$  collider. We observe the decays of  $B^+ \rightarrow \eta\pi^+$  and  $B^+ \rightarrow \eta K^+$ ; the measured branching fractions are  $\mathcal{B}(B^+ \rightarrow \eta\pi^+) = (4.8_{-0.7}^{+0.8}(\text{stat}) \pm 0.3(\text{sys})) \times 10^{-6}$  and  $\mathcal{B}(B^+ \rightarrow \eta K^+) = (2.1 \pm 0.6(\text{stat}) \pm 0.2(\text{sys})) \times 10^{-6}$ . Their corresponding  $CP$  violating asymmetries are measured to be  $0.07 \pm 0.15 \pm 0.03$  for  $\eta\pi^\pm$  and  $-0.49 \pm 0.31 \pm 0.07$  for  $\eta K^\pm$ . No significant signals are found for neutral  $B$  meson decays. We report the following upper limits on branching fractions at the 90% confidence level:  $\mathcal{B}(B^0 \rightarrow \eta K^0) < 2.0 \times 10^{-6}$ ,  $\mathcal{B}(B^0 \rightarrow \eta\pi^0) < 2.5 \times 10^{-6}$  and  $\mathcal{B}(B^0 \rightarrow \eta\eta) < 2.0 \times 10^{-6}$ .

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Charmless  $B$  decays provide a rich sample to understand the  $B$  decay dynamics and to search for  $CP$  violation. An unexpectedly large  $B \rightarrow \eta' K$  branching fraction has stimulated much theoretical interest. It was suggested even before the  $\eta' K$  measurement that two  $b \rightarrow s$  penguin amplitudes are constructive in  $B \rightarrow \eta' K$  decays but destructive in  $B \rightarrow \eta K$  [1]. The situation is reversed for  $B \rightarrow \eta' K^*$  and  $B \rightarrow \eta K^*$  decays. Experimental results have more or less confirmed this picture; however, precise measurements of branching fractions are needed to quantitatively understand the contribution of each diagram. It was also pointed out that the suppressed penguin amplitudes in the  $\eta K$  mode may interfere with the CKM suppressed  $b \rightarrow u$  (tree) amplitude and result in direct  $CP$  violation [2]. The penguin-tree interference may also be large in  $B^+ \rightarrow \eta' \pi^+$  [3] and  $B^+ \rightarrow \eta \pi^+$  decays although theoretical expectations on the partial rate asymmetry ( $A_{CP}$ ) could be either positive or negative [2, 4]. Recently, the BaBar collaboration has observed large negative  $A_{CP}$  values in both  $\eta K^+$  and  $\eta \pi^+$ , which are  $\sim 2\sigma$  away from zero [5]. However, more data are needed to verify these large  $CP$  violating asymmetries. Furthermore, branching fractions and  $A_{CP}$  in charmless  $B$  decays can be used to understand the tree and penguin contributions and provide constraints on the third unitarity triangle  $\phi_3$  [6].

In this paper, we report measurements of branching fractions and partial rate asymmetries for  $B \rightarrow \eta h$  decays, where  $h$  could be a  $K$ ,  $\pi$  or  $\eta$  meson. The partial rate asymmetry is defined as:

$$\mathcal{A}_{CP} = \frac{N(B^- \rightarrow f^-) - N(B^+ \rightarrow f^+)}{N(B^- \rightarrow f^-) + N(B^+ \rightarrow f^+)},$$

where  $N(B^-)$  is the yield for the  $B^- \rightarrow \eta h^-$  decay and  $N(B^+)$  denotes that of the charge conjugate mode. The data sample consists of 152 million  $B\bar{B}$  pairs ( $140 \text{ fb}^{-1}$ ) collected with the Belle detector at the KEKB  $e^+e^-$  asymmetric-energy (3.5 on 8 GeV) collider [7] operating at the  $\Upsilon(4S)$  resonance.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of a three-layer silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect  $K_L^0$  mesons and to identify muons (KLM). The detector is described in detail elsewhere [8].

Candidate neutral pions are selected by requiring the two-photon invariant mass to be in the mass window between  $115 \text{ MeV}/c^2$  and  $152 \text{ MeV}/c^2$ . The momentum of each photon is then readjusted, constraining the mass of the photon pair to be the nominal  $\pi^0$  mass. To reduce the low energy photon background, each photon is required to have a minimum energy of 50 MeV and the  $\pi^0$  momentum must be above  $250 \text{ MeV}/c$  in the laboratory frame. Two  $\eta$  decay channels are considered in this analysis:  $\eta \rightarrow \gamma\gamma$  ( $\eta_{\gamma\gamma}$ ) and  $\eta \rightarrow \pi^+\pi^-\pi^0$  ( $\eta_{3\pi}$ ). In the  $\eta_{\gamma\gamma}$  reconstruction, each photon is required to have a minimum energy of 50 MeV and the energy asymmetry, defined as the energy difference between the two photons divided by their energy sum, must be less than 0.9. Furthermore, we remove  $\eta$  candidates if either one of the daughter photons can pair with any other photon to form a  $\pi^0$  candidate. Candidate  $\eta_{3\pi}$  mesons are reconstructed by combining a  $\pi^0$  with a pair of oppositely charged tracks, originated from the interaction point (IP). We make the following requirements for the invariant mass (in  $\text{MeV}/c^2$ ) on the  $\eta$  candidates:  $516 < M_{\gamma\gamma} < 569 \text{ MeV}/c^2$  for  $\eta_{\gamma\gamma}$  and  $539 < M_{3\pi} < 556 \text{ MeV}/c^2$  for  $\eta_{3\pi}$ . An  $\eta$  mass constraint is implemented after the selection for each candidate.

Charged tracks are required to come from the IP. Charged kaons and pions directly from  $B$  decays are identified by combining information from the CDC ( $dE/dx$ ), the TOF and the ACC to form a  $K(\pi)$  likelihood  $L_K(L_\pi)$ . Discrimination between kaons and pions is achieved through the likelihood ratio  $L_K/(L_\pi + L_K)$ . Charged tracks with likelihood ratios greater than 0.6 are regarded as kaons, and less than 0.4 as pions. Furthermore, charged tracks that are positively identified as electrons or muons are rejected.  $K_S^0$  candidates are reconstructed from pairs of oppositely charged tracks with invariant mass ( $M_{\pi\pi}$ ) between 480 to 516 MeV/ $c^2$ . Each candidate must have a displaced vertex with a flight direction consistent with a  $K_S^0$  originating from the IP.

Candidate  $B$  mesons are identified using the beam constrained mass,  $M_{bc} = \sqrt{E_{\text{beam}}^2 - P_B^2}$ , and the energy difference,  $\Delta E = E_B - E_{\text{beam}}$ , where  $E_{\text{beam}}$  is run-dependent and determined from  $B \rightarrow D^{(*)}\pi$  events, and  $P_B$  and  $E_B$  are the momentum and energy of the  $B$  candidate in the  $\Upsilon(4S)$  rest frame. The resolutions on  $M_{bc}$  and  $\Delta E$  are around 3 MeV/ $c^2$  and  $\sim 20$ -30 MeV, respectively. Events with  $M_{bc} > 5.2$  GeV/ $c^2$  and  $|\Delta E| < 0.3$  GeV are selected for the final analysis.

The dominant background comes from the  $e^+e^- \rightarrow q\bar{q}$  continuum, where  $q = u, d, s$  or  $c$ . To distinguish signal from the jet-like continuum background, event shape variables and the  $B$  flavor tagging information are employed. We form a Fisher discriminant [9] from seven variables that quantify event topology. The Fisher variables include the angle  $\theta_T$  between the thrust axis [10] of the  $B$  candidate and the thrust axis of the rest of the event, five modified Fox-Wolfram moments [11] and a measure of the momentum transverse to the event thrust axis ( $S_\perp$ ) [12]. The probability density functions (PDF) for this discriminant and  $\cos\theta_B$ , where  $\theta_B$  is the angle between the  $B$  flight direction and the beam direction in the  $\Upsilon(4S)$  rest frame, are obtained using events in the signal Monte Carlo (MC) and data with  $M_{bc} < 5.26$  GeV/ $c^2$  for signal and  $q\bar{q}$  background, respectively. These two variables are then combined to form a likelihood ratio  $\mathcal{R} = \mathcal{L}_s/(\mathcal{L}_s + \mathcal{L}_{q\bar{q}})$ , where  $\mathcal{L}_{s(q\bar{q})}$  is the product of signal ( $q\bar{q}$ ) probability densities.

Additional background discrimination is provided by the  $B$  flavor tagging. We used the standard Belle  $B$  tagging package [13], which gives two outputs: a discrete variable  $q$  indicating the  $B$  flavor and a dilution factor ( $r$ ) ranging from zero for no flavor information and unity for unambiguous flavor assignment. We divide the data into six  $r$  regions. The continuum suppression is achieved by applying a mode dependent cut on  $\mathcal{R}$  for events in each  $r$  region based on  $N_s^{\text{exp}}/\sqrt{N_s^{\text{exp}} + N_{q\bar{q}}^{\text{exp}}}$ , where  $N_s^{\text{exp}}$  is the expected signal from MC and  $N_{q\bar{q}}^{\text{exp}}$  denotes the number of background events estimated in data. This  $\mathcal{R}$  requirement retains 58–86% of the signal while reducing 82–96% of the background. From MC all other backgrounds are found to be negligible except for the  $\eta K^+ \leftrightarrow \eta\pi^+$  reflection, due to  $K^+-\pi^+$  misidentification, and the  $\eta K^*(892)(\eta\rho(770))$  feed-down to the  $\eta K(\eta\pi)$  modes. We include these two components in a fit to extract the signal.

The signal yields and branching fractions are obtained using an extended unbinned maximum-likelihood (ML) fit with input variables  $M_{bc}$  and  $\Delta E$ . The likelihood is defined as:

$$\mathcal{L} = \exp\left(-\sum_j N_j\right) \prod_i^N \left[ \sum_j N_j P_j^i(M_{bc}, \Delta E) \right],$$

where  $N_j$  is the yield of category  $j$  (signal, continuum background, reflection,  $\eta K^*/\eta\rho$ ),  $P_j^i(M_{bc}, \Delta E)$  is the probability density for the  $i$ th event and  $N$  is the total number of events.



The PDFs of the signal, the reflection background and the  $\eta K^*/\eta\rho$  feed-down are modeled with two-dimensional  $M_{bc}$ - $\Delta E$  smooth functions obtained using MC. The peak positions and resolutions in  $M_{bc}$  and  $\Delta E$  are adjusted according to the data-MC differences using large control samples of  $B \rightarrow D\pi$  and  $\overline{D}^0 \rightarrow K^+\pi^-\pi^0/\pi^0\pi^0$  decays. The continuum background in  $\Delta E$  is described by a first or second order polynomial while the  $M_{bc}$  distribution is parameterized by an Argus function,  $f(x) = x\sqrt{1-x^2} \exp[-\xi(1-x^2)]$ , where  $x$  is  $M_{bc}$  divided by half of the total center of mass energy. The continuum PDF is the product of an Argus function and a polynomial, where  $\xi$  and the coefficients of the polynomial are free parameters. Since  $B \rightarrow \eta K^*$  decays were observed with relatively large branching fractions [14] ( $\sim 20 \times 10^{-6}$ ), their feed-down to the  $\eta K$  modes are fixed from MC in the likelihood fit. Since the decay  $B^+ \rightarrow \eta\rho^+$  is experimentally poorly constrained, the amount of this background in the  $\eta\pi$  modes is allowed to float in the fit. In the charged  $B$  modes, the normalizations of the reflections are fixed to expectations based on the  $B^+ \rightarrow \eta K^+$  and  $B^+ \rightarrow \eta\pi^+$  branching fractions and  $K^+ \leftrightarrow \pi^+$  fake rates, measured using  $\overline{D}^0 \rightarrow K^+\pi^-$  data. The reflection yield is first estimated with the assumed  $\eta K^+$  and  $\eta\pi^+$  branching fractions and is then recalculated according to our measured branching fractions. No  $B\overline{B}$  contributions are considered for the  $B^0 \rightarrow \eta\eta$  mode.

In Table I for each decay mode we show the measured branching fractions as well as other quantities associated with the measurements. The efficiency for each mode is determined using MC simulation and corrected for the discrepancy between data and MC using the control samples. The only discrepancy we find is the performance of particle identification, which results a 4.3% correction for the  $\eta\pi^+$  mode and 1.7% for  $B \rightarrow \eta K^+$ . The combined branching fraction of the two  $\eta$  decay modes is obtained from a simultaneous likelihood fit to all the sub-samples with a common branching fraction. The statistical error in the signal yield is taken as the change in the central value when the quantity  $-2 \ln \mathcal{L}$  increases by one unit from its minimum value. The statistical significance is taken as the square root of the difference between the value of  $-2 \ln \mathcal{L}$  for zero signal yield and the minimum value. The number of  $B^+B^-$  and  $B^0\overline{B}^0$  pairs are assumed to be equal.

Systematic uncertainties in the fit due to the knowledge of the signal PDFs are estimated by performing the fit after varying their peak positions and resolutions by one standard deviation. In the  $\eta K$  modes, we also vary the expected  $\eta K^*$  feed-down by 1 standard deviation to check the yield difference. The quadratic sum of the deviations from the central value gives the systematic uncertainty in the fit, which ranges from 3% to 6%. The performance of the  $\mathcal{R}$  cut is studied by checking the data-MC efficiency ratio using the  $B^+ \rightarrow \overline{D}^0\pi^+$  control sample. The obtained error is 2.4-3.5%. The systematic errors on the charged track reconstruction are estimated to be around 1% using partially reconstructed  $D^*$  events, and verified by comparing the ratio of  $\eta \rightarrow \pi^+\pi^-\pi^0$  to  $\eta \rightarrow \gamma\gamma$  in data with MC expectations. The  $\pi^0$  and  $\eta_{\gamma\gamma}$  reconstruction efficiency is verified by comparing the  $\pi^0$  decay angular distribution with the MC prediction, and by measuring the ratio of the branching fractions for the two  $\eta$  decay channels:  $\eta \rightarrow \gamma\gamma$  and  $\eta \rightarrow \pi^0\pi^0\pi^0$ . We assign 3.5% error for the  $\pi^0$  and  $\eta_{\gamma\gamma}$  reconstruction. The  $K_S^0$  reconstruction is verified by comparing the efficiency ratio of  $D^+ \rightarrow K_S^0\pi^+$  and  $D^+ \rightarrow K^-\pi^+\pi^+$ . The  $K_S^0$  detection systematic error is 4.4%. The uncertainty of number of  $B\overline{B}$  events is 1%. The final systematic error is obtained by first summing all correlated errors linearly and then quadratically summing the uncorrelated errors.

Figure 1 shows the  $M_{bc}$  and  $\Delta E$  projections after requiring events to satisfy  $-0.1 < \Delta E < 0.08$  GeV ( $-0.15 < \Delta E < 0.1$  GeV for the  $\eta_{\gamma\gamma}$  and  $\eta\pi^0$  modes) and  $M_{bc} > 5.27$

TABLE I: Detection efficiency, product of daughter branching fractions, yield, statistical significance, measured branching fraction, the 90% C.L. upper limit and  $A_{CP}$  for the  $B \rightarrow \eta h$  decays. The first errors on columns 4, 6 and 8 are statistic and the second errors are systematic.

Mode	$\epsilon(\%)$	$\prod \mathcal{B}_i(\%)$	Yield	Sig.	$\mathcal{B}(10^{-6})$	UL( $10^{-6}$ )	$A_{CP}$
$B^+ \rightarrow \eta \pi^+$				8.1	$4.8 \pm 0.7 \pm 0.3$		$0.07 \pm 0.15 \pm 0.03$
$\eta_{\gamma\gamma} \pi^+$	23.3	39.4	$73.4^{+13.5}_{-12.7} \pm 2.0$	7.2	$5.3^{+1.0}_{-0.9} \pm 0.3$		$0.11 \pm 0.17 \pm 0.03$
$\eta_{3\pi} \pi^+$	14.8	22.6	$19.6^{+7.0}_{-6.1} \pm 0.7$	4.0	$3.8^{+1.4}_{-1.2} \pm 0.3$		$-0.11^{+0.35+0.04}_{-0.33-0.05}$
$B^+ \rightarrow \eta K^+$				4.0	$2.1 \pm 0.6 \pm 0.2$		$-0.49 \pm 0.31 \pm 0.07$
$\eta_{\gamma\gamma} K^+$	21.1	39.4	$28.0^{+10.0}_{-9.1} \pm 1.6$	3.5	$2.2^{+0.8}_{-0.7} \pm 0.2$		$-0.45^{+0.35}_{-0.31} \pm 0.07$
$\eta_{3\pi} K^+$	13.8	22.6	$7.4^{+5.4}_{-4.5} \pm 0.5$	1.8	$1.5^{+1.1}_{-0.9} \pm 0.2$		$-0.78^{+1.03+0.11}_{-0.76-0.12}$
$B^0 \rightarrow \eta K^0$				0.4	$0.3^{+0.9}_{-0.7} \pm 0.1$	< 2.0	
$\eta_{\gamma\gamma} K^0$	22.9	13.5	$-1.9^{+4.3}_{-3.1} \pm 0.3$	—	$-0.4^{+0.9}_{-0.7} \pm 0.1$		
$\eta_{3\pi} K^0$	12.2	7.8	$3.5^{+3.6}_{-2.7} \pm 0.2$	1.4	$2.4^{+2.5}_{-1.9} \pm \pm 0.3$		
$B^0 \rightarrow \eta \pi^0$				1.9	$1.2 \pm 0.7 \pm 0.1$	< 2.5	
$\eta_{\gamma\gamma} \pi^0$	17.0	39.0	$18.2^{+8.9+0.8}_{-8.0-0.7}$	2.5	$1.8^{+0.9}_{-0.8} \pm 0.2$		
$\eta_{3\pi} \pi^0$	11.2	22.3	$-3.0^{+5.0}_{-4.0} \pm 0.3$	—	$-0.8^{+1.3}_{-0.8} \pm 0.1$		
$B^0 \rightarrow \eta \eta$				1.2	$0.7^{+0.7}_{-0.6} \pm 0.1$	< 2.0	
$\eta_{\gamma\gamma} \eta_{\gamma\gamma}$	16.9	15.5	$-1.5^{+2.7}_{-1.6} \pm 0.1$	—	$-0.4^{+0.7}_{-0.4} \pm 0.0$		
$\eta_{\gamma\gamma} \eta_{3\pi}$	11.3	17.8	$7.3^{+4.5}_{-4.0} \pm 0.2$	2.3	$2.3^{+1.4}_{-1.2} \pm 0.2$		
$\eta_{3\pi} \eta_{3\pi}$	7.7	5.1	$0.3^{+2.0}_{-1.2} \pm 0.1$	0.2	$0.5^{+3.1}_{-1.9} \pm 0.1$		

GeV/ $c^2$ , respectively. No significant signals are observed for the neutral  $B$  meson modes; we set their branching fraction upper limits at the 90% confidence level. The upper limit for each mode is determined using the combined likelihood with the reconstruction efficiency reduced by its systematic error. We vary the signal PDF and the expected  $\eta K^*$  feed-down in the  $\eta K^0$  mode to compute the likelihood; the largest branching fraction that covers 90% of the likelihood area is chosen to be the upper limit.

Significant signals are observed for charged  $B$  decays and we investigate their partial rate asymmetries by extracting signal yields separately from the  $B^+$  and  $B^-$  samples. A likelihood fit is performed independently for the two  $\eta$  decay modes. The same signal and background PDFs used in the branching fraction measurement are applied. The parameters of the continuum PDF are fixed according to the branching fraction results. Contributions from  $B\bar{B}$  backgrounds are required to be equal for the  $B^+$  and  $B^-$  samples. Figure 2 shows the  $M_{bc}$  and  $\Delta E$  projections. The  $A_{CP}$  results for the two  $\eta$  decay modes are combined assuming that the errors are Gaussian. Systematic errors that arise from the knowledge of the signal PDF are estimated by varying the peak positions and resolutions. We also check the  $A_{CP}$  values after varying the amount of the expected  $\eta K^*$  feed-down and the reflection background. The  $B\bar{B}$  contributions are allowed to be different for the two samples to obtain the systematic error. The largest uncertainty is caused by the reflection. A possible detector bias in  $A_{CP}$  is studied using  $B \rightarrow D\pi^+$  decays. The obtained uncertainty is 0.5%. Each  $A_{CP}$  deviation is added quadratically to provide the total systematic uncertainty.

In summary, we have observed both  $B^+ \rightarrow \eta \pi^+$  and  $B^+ \rightarrow \eta K^+$  decays. Their measured branching fractions and partial rate asymmetries are summarized in Table I. We conclude

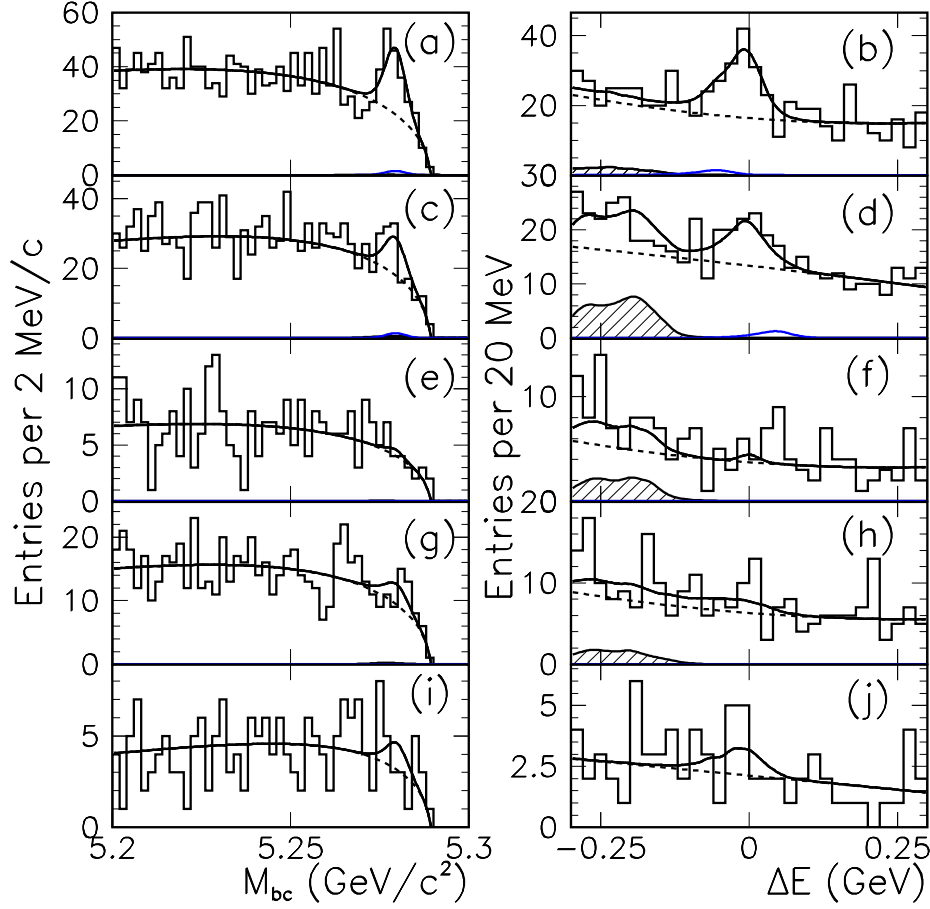


FIG. 1:  $M_{bc}$  and  $\Delta E$  projections for (a,b)  $B^+ \rightarrow \eta\pi^+$ , (c,d)  $B^+ \rightarrow \eta K^+$ , (e,f)  $B^0 \rightarrow \eta K^0$ , (g,h)  $B^0 \rightarrow \eta\pi^0$  and (i,j)  $B^0 \rightarrow \eta\eta$  decays with the  $\eta_{\gamma\gamma}$  and  $\eta_{3\pi}$  modes combined. Open histograms are data, solid curves are the fit functions, dashed lines show the continuum contributions and shaded histograms are the  $\eta K^*/\eta\rho$  contributions. The small contributions around  $M_{bc} = 5.28 \text{ GeV}/c^2$  and  $\Delta E = \pm 0.05 \text{ GeV}$  in (a)-(d) are the backgrounds from  $B^+ \rightarrow \eta\pi^+$  and  $B^+ \rightarrow \eta K^+$ .

that the  $\eta\pi^+$  branching fraction is larger than that of  $\eta K^+$ . Our measured  $B^+ \rightarrow \eta\pi^+$  branching fraction is consistent with the BaBar result; however, unlike the large negative  $A_{CP}$  observed by BaBar, our central value is small and positive but is consistent with no asymmetry. For the decay  $B^+ \rightarrow \eta K^+$ , our measured branching fraction is 40% lower than the BaBar result, corresponding to a  $1.3 \sigma$  deviation. Interestingly, both experiments suggest a large negative  $A_{CP}$  value for  $B^+ \rightarrow \eta K^+$ , which is anticipated by some theories [15]. No significant signals are found in the neutral  $B$  meson decays and we give their upper limits at the 90% confidence level.

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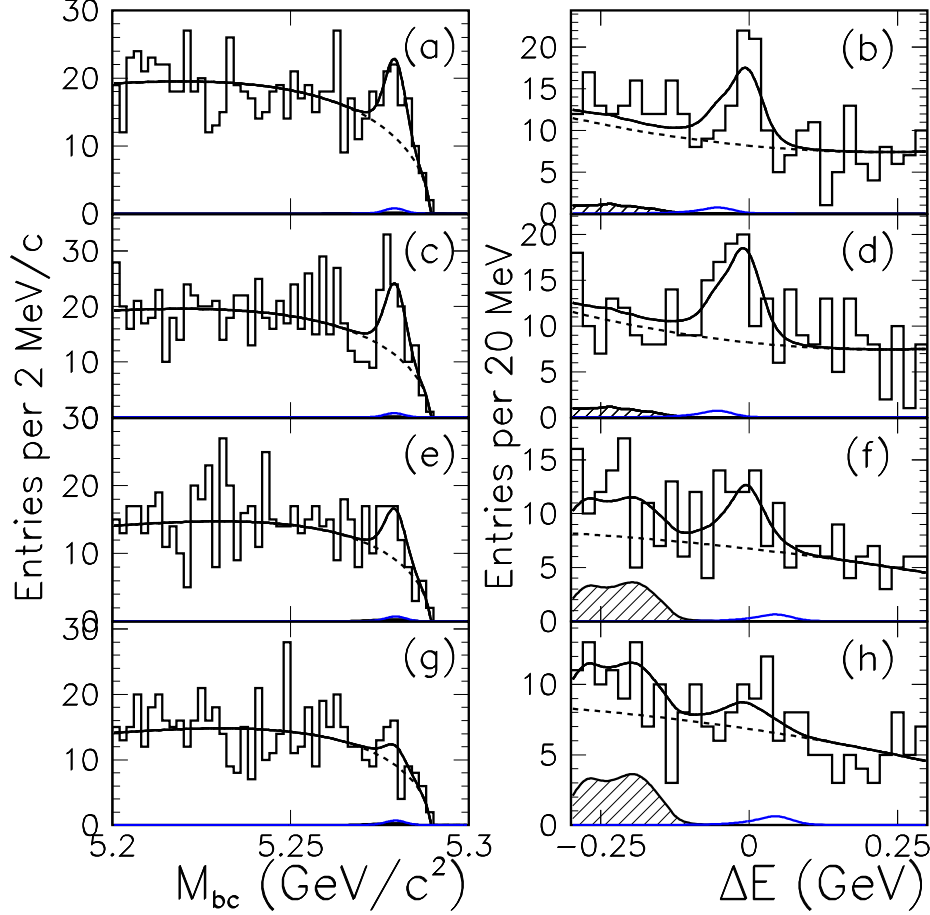


FIG. 2:  $M_{bc}$  and  $\Delta E$  projections for (a,b)  $B^+ \rightarrow \eta\pi^+$ , (c,d)  $B^- \rightarrow \eta\pi^-$ , (e,f)  $B^+ \rightarrow \eta K^+$ , and (g,h)  $B^- \rightarrow \eta K^-$  with the  $\eta_{\gamma\gamma}$  and  $\eta_{3\pi}$  modes combined. Open histograms are data, solid curves are the fit functions, dashed lines show the continuum contributions and shaded histograms are the  $\eta K^*/\eta\rho$  contributions. Small curves around  $M_{bc} = 5.28 \text{ GeV}/c^2$  and  $\Delta E = \pm 0.05 \text{ GeV}$  are the reflection background on  $B^+ \rightarrow \eta\pi^+$  and  $B^+ \rightarrow \eta K^+$ .

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